International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN (P): 2249–6890; ISSN (E): 2249–8001
Vol. 10, Issue 2, Apr 2020, 191–200

INVESTIGATION THE GRAIN-BOUNDARY CORROSION AND CRACKING ON STAINLESS STEEL A316 PROCESSED BY EDM DIE-SINKER FOR THE FOOD AND MEDICINES INDUSTRY

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ABSTRACT

Stainless-steel A316 is widely utilized in the medicine and food industry not only because of its excellent material characteristics: hard, high fatigue strength, wear-resistance and corrosion-resistance but also because it meets health standards. However, due to the complicated forms of dies and punches, a conventional machining is limited to process this material. To tackle the limitation of the conventional machine, the sinker EDM (electrical discharge machining) which uses spark energy with a large electric current density can be used. Strongly influenced by the process parameters, including discharge current, pulse-on-time, servo sensitivity, and electrode material, EDM brought some disadvantages such that the surface and it's below are susceptible to the grain boundaries corrosion and crack. Grain boundary corrosion and cracking on A316 processed by EDM has not been further explored yet. This research aims to investigate the corrosion and crack form in dies and punches of stainless steel A316 processed by EDM. Based on the result, the grain boundary corrosion and cracking appeared in both surface and recast layer of A316, which processed by the EDM with 6A and copper electrode. This corrosion and cracking can reduce the lifetime and health considered of punch and dies.

KEYWORDS: AISI 316, Sinker EDM, Machining Parameters & Smoothness

Received: Jan 28, 2020; **Accepted:** Feb 18, 2020; **Published**: Feb 26, 2020; **Paper Id**.: IJMPERDAPR202017

Original Article

INTRODUCTION

A compacting process using dies and punches is widely applied for medicinal and food processing to form tablets (Mohan 2012) (Bare et al. 2011). Dies and punches should be free from corrosion and cracking to ensure health requirements. The corrosion risk reacts chemically with medicinal or food ingredients, which able to affect the identity, quality, and purity of those products. Corrosion can also harm human health if they enter the body. Consequently, dies and punches material and processing for medicinal and food must suffice health safety standards to avoid health risks and hazards.

Refer to BPOM (the Republic of Indonesia Medicine and Food Supervisory Agency) chapter 4.2 and 4.7, equipment surfaces that contact with raw materials, intermediate products, or finished products may not cause reactions to both additions or absorption that can affect identity, quality, or purity beyond the specified requirements. Furthermore, the production equipment in which contact with the product must not harm, reactive, additive, or absorbent, which can affect the quality and adversely affect the product.

Besides chemical reaction on the surface, corrosion and crack appearing at below surface layer of dies and punches can shorten the lifetime. It is because they can reduce the strength of the material. Tool steel and stainless steel are materials commonly used for dies and punches because of their properties such as hard, high wear-

resistant, and deformation-resistant. However, tool steels are not fit for medicinal and food products because they react chemically with the ingredients. Thus, the suitable materials for these purposes are austenitic stainless-steels. However, it needs further analysis, mainly the fabricating.

Fabricating of dies and punches for hard materials and complicated shapes are intricated to implement with ordinary conventional CNC-machining (Sorgaton, Masato, and Lucchetta, 2017)(Kiyak, and Çakir, 2007). Therefore, non-conventional machining processes, such as electric discharge machine (EDM) processes have an essential role in these dies and punches manufacturing (Singh and Singh, 2012). EDM is a non-conventional process that uses spark energy with a large electric current between the machine tool (cathode) and the workpiece (anode) for the metal removal process (Vishwakarma, Khare, and Parashar, 2012). EDM sinker process is susceptible to the type of machine, changes in process parameters such as discharge current, electrode materials, pulse on time, servo sensitivity, and the type of material. In EDM, spark with a temperature around 10,000oC will leave the cutting crater, increase surface hardness, and crack on the surface. Stainless steels are material which have excellent corrosion resistance because of protective oxide film formed on the surface. However, stainless steel severe to corrosion because of carbide precipitation $Cr_{23}C_6$ at the grain boundaries due to the high-temperature of the EDM process.

Based on the above background, this research is a crucial aim to investigate the corrosion and crack regarding the parameters used in the EDM process. Therefore, appropriate process parameters to minimize the corrosion and crack in the dies and punches that processed by EDM can be chosen. A316 is stainless steel which suspects to grain boundary corrosion while exposed at high temperatures. In this research, analysis of crack and grain boundary corrosion on A316 processed by EDM was conducted. Grain boundary corrosion and cracking in stainless steel A316 processed by EDM has not been further explored yet.

LITERATURE REVIEW

EDM (Electrical Discharge Machining) is a non-conventional machining widely applied in die and mold making industries to fabricate deep and complex cavity (Chakraborty, Dey, and Ghosh, 2014). Unlike conventional machining techniques that use cutting tools, EDM machines form a workpiece by releasing an electric arc (spark discharge) through two electrodes (Razak et al., 2016). This electric arc causes hugely high heat (around 10,000oC) so that the material will melt then rapid cooling and erode when the flushing of dielectric fluid applied. The schematic of the EDM-sinker machine is shown in Figure 1. The EDM cutting process produces craters, erosion in the surface and different heat treatment below the surfaces as shown in Figure 2.

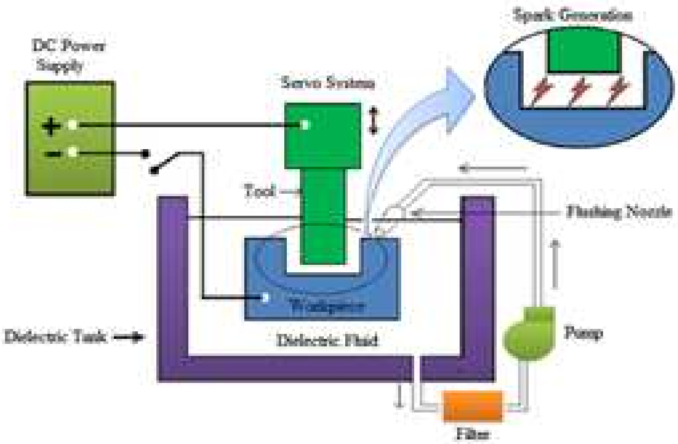

Figure 1: Schematic Diagram of the EDM Process (Mandaloi et al., 2016).

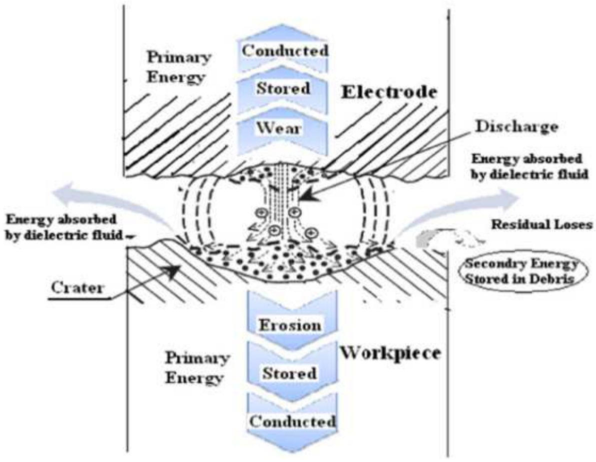

Figure 2: Schematic of EDM die-sinker cutting (Sandeep, 2013).

EDM is suitable for cutting the materials with the following properties: sturdy and soft, very brittle, heat-treated part, part with complicated shapes, and conductor (Engelita, Yuhas, and Muslimin, 2019). In the past, some research has been conducted on the effect of EDM sinking parameters on various performance parameters. The effect of discharge and servo sensitivity parameters in the surface smoothness of the EDM sinker of SKD 11 material for dies (Andriani, Sumpena, and Muslimin, 2018). Based on the research, roughness increases in proportion to the discharge current. Examination of machining parameters of current, pulse on time, and pulse off time for processing tool steel AISI P20 using copper electrodes concluded that roughness was increase related to electric current (Kiyak and Çakir, 2007). Harpreet Singh, et al. compared surface roughness and electrode wear with different types of electrodes (Copper, Brass, Cryogenic Copper, Cryogenic Brass) and used current parameters (Singh and Singh, 2012). The material used was H12 Die-Steel. From this research, the result is that the roughness increases with increasing the electric current, and the electrode wear affects the resulting roughness.

Sultan, Kumar, and Gupta (2014) compared MRR, electrode wear, surface roughness, and SEM with the ANOVA method. The parameters used were current, pulse off time, and on-time. In this research, material EN 353 Alloy steel and copper electrodes were used. The pulse on time and off time affects electrode wear. An electric current influences the surface roughness (Kumar and Garg 2010). In this study, surface roughness is compared with the ANOVA method. The parameters used in this method are discharge current, pulse on, and off time. The material used was A316, and the electrode was copper. The increase in electric current influences the surface roughness (Razak et al., 2016). In the study, surface roughness is compared based on current, voltage, pulse on-time, and off-time parameters. The electrodes used are copper and AZ31 Magnesium Alloy as the material being examined. The pulse on-time very influenced surface roughness (Singh and Singh, 2012).

Furthermore, there were published works on the analysis and evaluation of heat-affected zones (HAZ) workpiece surfaces machined by using different electrodes of EDM (Kumar and Garg 2010). In this working, various essential parameters such as pulse on and off, peak current, and discharge gap of EN-31 steel was applied. Ashok Kumar, Laxminarayana, and Aravinda (2017) investigated the optimum values of the significant parameters in micromachining of Stainless Steel, A316 by Die Sinker EDM process by using a 900 µm with the circular copper electrode (Ashok Kumar, Laxminarayana, and Aravindan, 2017). The discharge current, pulse-on time, and pulse-off time, the gap was selected as the process parameters. The result concludes that the EDM machined surface of A316 resulted in micro-cracks and pores caused

by the high-temperature gradient, which reduces both the precision and operating life of the machine tooling. Therefore, by choosing the suitable machining parameters, the corrosion and crack can be avoided or minimized from worked parts.

RESEARCH METHODS

Specimens, EDM Machine and Electrode

The material used was stainless steel A316 food grade with a size of 80 mm x 50 mm x 10 mm for six samples. The chemical compositions of this material is 0.024% C, 0.001% S, 0.025%P, 1.29% Mn, 0.46% Si, 16-16.6% Cr, 10-10.1%Ni, 2-2.06 % Mo and 0.05%N (percentage in weight).

The electrodes used are copper with specifications, as shown in Table 1.

Table 1: Copper Electrode Specifications

Properties	Copper (99% pure)
Melting point (^oC)	1083
Density (g/cm^3)	8,96
Thermal Conductivity (W/m-K)	391
Electrical resistivity (Ω-cm)	1.69
Specific heat capacity (J/g-^oC)	0,385

Experiment set up

The tool set up in this research is shown in Figure 3. The machine was a CNC-EDM Die Sinker of SKM, which has a maximum capacity of 25A discharge current working. The fixed process parameters used were a pulse on time, pulse off time, gap voltage, servo sensitivity, gap distance, and dialectical fluids of CPC Kerosene. The parameters set in this research were shown in Table 2. The 6A discharge current and the copper electrode are applied in this research. This parameter's value was selected based on the previous author experiment (Engelita, Yuhas, and Muslimin, 2019)(Andriani, Sumpena, and Muslimin, 2018).

Table 2: Fixed Parameters of EDM

Fixed Parameters	Symbols	Unit	Value
Pulse on Time	Ton	μsec	120
Pulse off Time	Toff	μsec	3
Gap Voltage	V	Volts	45
Servo Sensitivity	SVO	1/min	5
Gap distance		mm	0.02-0.1
Dielectric Fluid	CPC Kerosene		
Type of EDM	Sinker SKM EDM		

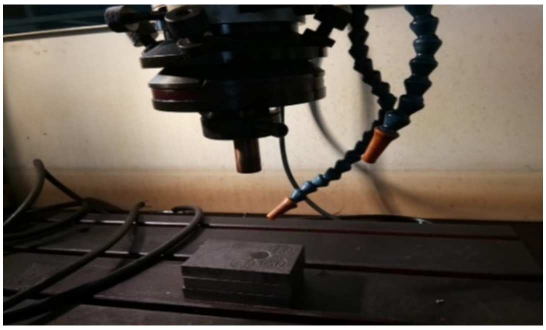

Figure 3: An EDM Experimental Setup.

The research specimen before the EDM process is shown in Figure 4(a) and after the EDM process is shown in Figure 4(b).

(a) (b)

Figure 4: A Specimen before EDM Processing (dimension of 80 mm x 50 mm x 10mm): (a) before and (b) after.

Experiment schemes in this research were tested by Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS). Scanning Electron Microscope (SEM) was applied to analyze a microstructure of material while Energy Dispersive Spectroscopy (EDS) to analyze the chemical composition of the material.

FINDINGS AND DISCUSSIONS

Figure 5 shows the SEM image of the A316 food-grade before the EDM process. It shows that neither grain boundary corrosion nor crack appears in this material. Figure 6 shows the EDS of A316 Food grade. Based on the EDS result, the chemical composition of A316 is relatively the same as the catalog. The chemical compositions on the surface before the EDM process are 0.60%Si, 15.13%Cr, 1.59%Mn, 9.28%Ni, and 1.55%Mo (percentage of weight).

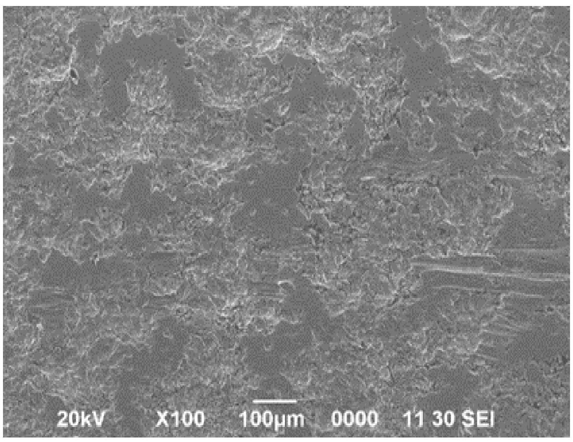

Figure 5: SEM Image of A316 Food-Grade before EDM Process.

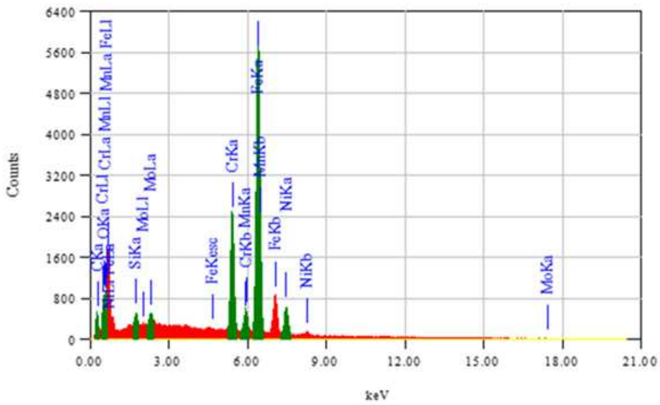

Figure 6: EDS of A316 Food-Grade before EDM Process.

Figure 7 shows the SEM image of the A316 surface processed by EDM with a 6A discharge current and copper electrode. Based on Figure 7, crates and recasts are formed due to high temperatures resulted from discharge currents of the EDM process. The hole and lumps (globule) also produced in this process. These phenomena are a typical behavior of the EDM process. The EDS analysis of material after processing is shown in Figure 8. The chemical compositions on the surface after the EDM process are 16.26%Cr, 1.45%Mn, and 10.07%Ni (percentage of weight). Based on the EDS analysis, there was an increase in the percentage of Chromium (from 15.13% to 16.26%) on the surface. It can be indicated that there were Cr concentrations on the surface due to the heating process of EDM.

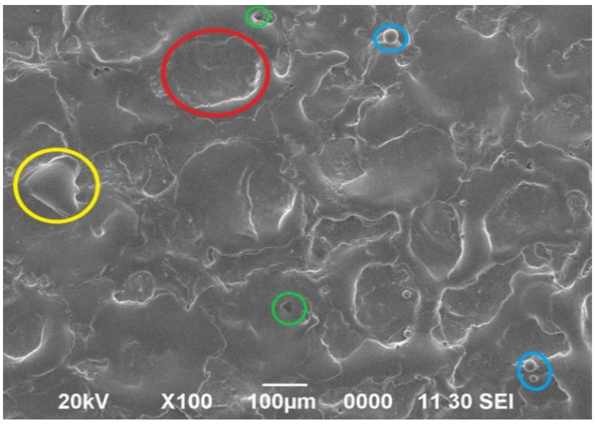

Figure 7: SEM of EDM Process with 6A.
Note: yellow: recast; red: crates; green: globule; green: hole

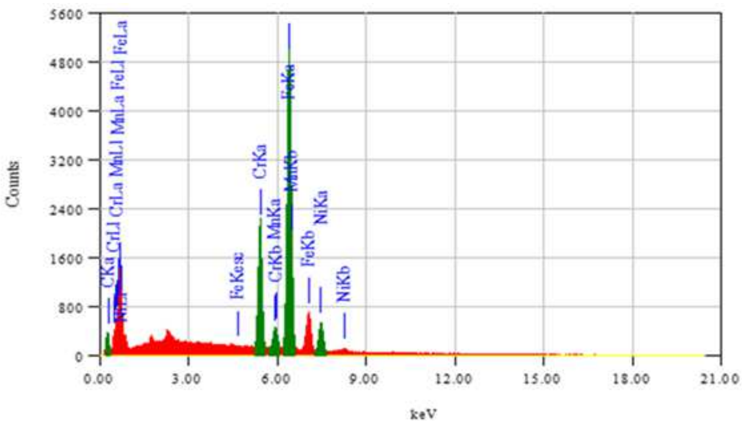

Figure 8: EDS Analysis of Surface after the EDM Process.

The microstructure of steels, including stainless steel A316, will change due to the solidification and heat treatment process. The EDM process produced different effects on surface layers because of the differentiated of heat-affected from discharge energy. Figure 9 shows the surface layer of material processed by the EDM sinker (Minna, 2011). The top layer, called as a spattered EDM, is the surface with 1-40 µm of thickness. The second layer is the recast layer or hardened layer with 200µm of thickness. The third layer is the heat-affected zone or annealed layer with 200µm of thickness. The last is base metal. The first of three surface layers is called an altered metal zone. The thickness of each layer is influenced by EDM parameters set up and target material.

To investigate the corrosion and crack under the surface layer, SEM and EDS tests were carried out in the area. Figure 10 shows SEM on the recast layer, while Figure 11 shows the EDS analysis in this area.

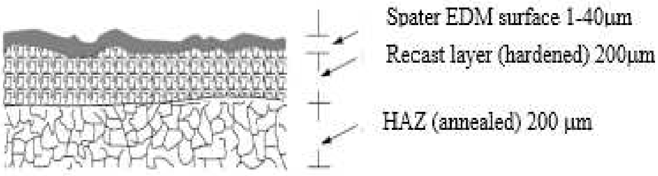

Figure 9: The Thickness of Each Layer (Minna, 2011)

Based on SEM analysis, the enrichment of Cr23C6 was formed on the grain boundary of the recasting layer microstructure. While, EDS analysis shows the chemical compositions on the recast layer after the EDM process is 15.99%Cr, 1.79%Mn, 1.61%Mo, and 9.85%Ni (percentage of weight). Based on this EDS analysis, there was Cr enrichment (from 15.13% to 15.99%) on the recast layer. This enrichment worsens the pitting corrosion resistance properties in the boundary as the sensitization. A crack appeared since the corrosion deep and link to each other. Cl and O elements appeared in the recasting layer as a reaction with dielectric fluids at high temperatures. The formation of precipitation Cr23C6 was significantly detriment the formation of the passive layer to resisting corrosion attack in medium containing chloride anion (Rashid et al., 2012)

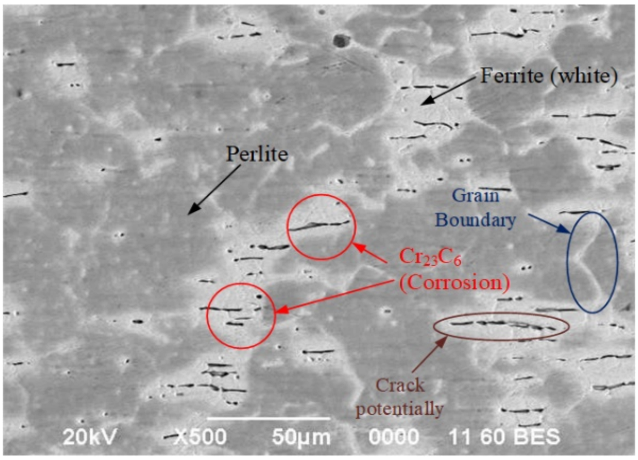

Figure 10: SEM of the Recast Layer of 6A

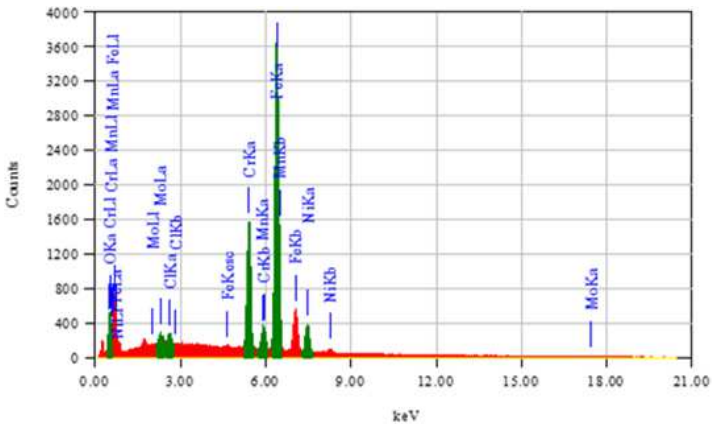

Figure 11: EDS of Ecasting Layer

Stainless steels are the type of steel that has excellent corrosion resistance and weldability properties. This material has been widely used in the industry. These materials contain a high level of chromium (16-16.6%), which forms a protective oxide film on the surface hence resisting corrosion. The oxide film regenerates when damaged, making the steel stainless. However, carbide precipitation Cr23C6 formed in high temperatures can ignite the occurrence of chromium-depleted zones at the grain boundaries. This phenomenon is known as sensitization, in which the severe corrosion takes place at the zones (Atanda, Fatudimu, and Oluwole, 2010) (Srisuwan et al., 2016). Therefore, because of the grain boundary corrosion and cracking occurred, it will reduce the lifetime and health considered of punches and dies.

CONCLUSIONS

This experiment was conducted to investigate crack and grain boundary corrosion on material A316 which processed with EDM for food and medicine industry application. Based on the result, the grain boundary corrosion and cracking are unable to escape in both the surface and recast layer of A316. However, because the proportion is tiny (in the small area), the material A316 is safe to process by EDM with 6A discharge current and copper electrode for dies and punches for food and medicinal industry. Thus, by using the appropriate parameters in this research, EDM can be applied for fabricating dies sinker for A316 with EDM process.

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